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Abstract

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PHYSICS

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SCHOTTKY EMISSION AND CURRENTS IN DIELECTRICS

1. The distinction between the problems of the current regime of a dielectric with a constant contact barrier φ_0^* and with lowering of the barrier by the field $(^{1,2})^*$

$$\varphi^* = \varphi_0^* - q\sqrt{-qE_1^*/\chi} \quad (1)$$

reduces to a change in the boundary conditions, which, when the Schottky effect is taken into account, assume, in dimensionless notation, the form*

$$n_0 = e^{\sqrt{-aE_1}}, \quad n_L = n_2, \quad (2)$$

where

$$a = \frac{q^2}{\chi kT} \frac{1}{x_{\text{Deb}}^*} = \frac{q^3}{\chi kT} \sqrt{\frac{4\pi n_{00}^*}{\chi kT}} = \frac{1}{4\pi x_{\text{Deb}}^{*3} n_{00}^*}. \quad (3)$$

Consequently, the influence of the Schottky effect on the general solution of the problem of emission currents in a dielectric $(^3)$

$$n = \sqrt{\frac{9j^2 u^2}{2} \left[\left(\frac{Z_{-2/3}(u)}{Z_{1/3}(u)} \right)^2 + 1 \right]}; \quad E = \sqrt[3]{6ju} \frac{Z_{-2/3}(u)}{Z_{1/3}(u)};$$

$$V = 2 \ln \left| \frac{u_0^{1/3} Z_{1/3}(u_0)}{\gamma u_L^{1/3} Z_{1/3}(u_L)} \right| \quad (4)$$

is manifested in the fact that the current functions $C(j)$ and $B(j)$, entering into

$$Z_{1/3}(u) = \begin{cases} N_{1/3}(u) + BJ_{1/3}(u), & \text{for } C + jx > 0, \\ K_{1/3}(w) + B'I_{1/3}(w), & \text{for } C + jx < 0; \end{cases} \quad (5)$$

$$Z_{-2/3}(u) = \begin{cases} N_{-2/3}(u) + BJ_{-2/3}(u), & \text{for } C + jx > 0, \\ -i[K_{-2/3}(w) - B'I_{-2/3}(w)], & \text{for } C + jx < 0, \end{cases} \quad (6)$$

where

$$u = \frac{\sqrt{2}}{3|j|}(C + jx)^{3/2} = -i \frac{\sqrt{2}}{3|j|}(-C - jx)^{3/2} = -iw. \quad (7)$$

We shall consider the voltage range where

$$w_L \equiv \frac{\sqrt{2}}{3|j|}(-C + |j|L)^{3/2} \geq 5. \quad (8)$$

In this case ⁽⁴⁾

$$B(j) \equiv -\sqrt{3} + \frac{2}{\pi}B'(j) \approx -\sqrt{3}, \quad (9)$$

i.e., it is practically independent of j , and only one current function $C(j)$ enters the expression for the current-voltage characteristic. This function is deter-

* The notation and units are the same as in ^(3,4). The discussion is carried out for emission from a metal into the conduction band of a dielectric (electron emission), when the Schottky effect arises for $E_1^* < 0$. The unit of measurement of the concentration n_{00}^* corresponds to the electron concentration at the source (cathode) in the dielectric for a barrier height φ_0^* .

is obtained from the boundary condition at the emitting contact, which leads to the equation

$$C \left[\left(Z_{-2/3}(u_0)/Z_{1/3}(u_0) \right)^2 + 1 \right] = \exp \sqrt{-a \sqrt[3]{6ju_0} Z_{-2/3}(u_0)/Z_{1/3}(u_0)}, \quad (10)$$

where

$$u_0 = \frac{\sqrt{2}}{3|j|} C^{3/2} = -iw_0. \quad (11)$$

The system (10) and (11) determines C as a function of j for given values of L and a , i.e., for given values of L^* and φ_0^* .

2. To study and compare the current functions $C(j)$ with and without allowance for the Schottky effect, we write the boundary condition (2) at the emitting contact in the form of three equations (see also the expression for n in (4), where $\sqrt[3]{9j^2u_0^2/2} = C$):

$$E_1 = -\frac{1}{a} \ln^2 n_0; \quad C \left[1 + \left(\frac{Z_{-2/3}(u_0)}{Z_{1/3}(u_0)} \right)^2 \right] = n_0; \quad u_0 = \frac{\sqrt{2}}{3|j|} C^{3/2}. \quad (12)$$

These expressions, together with the first integral of the system of kinetic equations (see (3)),

$$n_0 - E_1^2/2 = C \quad (13)$$

make it possible to eliminate u_0 , E_1 , and n_0 , and to represent C as a function of j for given L and a . Making the change of variables

$$j = \tilde{j} n_0^{3/2}; \quad C = \tilde{C} n_0; \quad E_1 = \tilde{E}_1 n_0^{1/2}, \quad (14)$$

we arrive at the system

$$1 - \frac{1}{2a^2} \frac{\ln^4 n_0}{n_0} = \tilde{C}; \quad \frac{1}{\tilde{C}} = 1 + \left(\frac{Z_{-1/3}(u_0)}{Z_{1/3}(u_0)} \right)^2; \quad u_0 = \frac{\sqrt{2}}{3|\tilde{j}|} \tilde{C}^{3/2}, \quad (15)$$

the last two equations of which coincide with the equations for $C(j)$ in the absence of the Schottky effect (see (3), (4)), while the first equation describes the relation of $\tilde{C}$ to the change in the boundary concentration n_0 , which is absent if the electric field does not affect the contact barrier ($a = 0$; $n_0 = 1$). Consequently, the function $\tilde{C}(\tilde{j})$, found from the last two equations (15), coincides with the function $C(j)$ calculated in (4) for the problem of emission currents with constant work function from the source. This makes it possible to find $\tilde{C}(\tilde{j})$ directly for any prescribed value of $\tilde{j}$. Knowing $\tilde{C}(\tilde{j})$, we then find, with the aid of the first equation (15), the corresponding value of n_0 for any specified a (Fig. 1). For convenience in considering the regions of positive values of $\tilde{C}$, the scales for $\tilde{C} > 0$ and for $\tilde{C} < 0$, and also for $|\tilde{j}| < 1.825$ and for $|\tilde{j}| > 1.825$, have been chosen differently. Since for $|\tilde{j}| < 0.688$ the contact field in the dielectric is $E_1 > 0$ and there is no Schottky emission, the origin along the $|\tilde{j}|$ axis is taken to be $|\tilde{j}| = 0.688$.

For all $a \neq 0$, the interval of variation of $\tilde{C}$ is bounded and lies between $\tilde{C} = 1$ and

Fig. 1

Figure 1: Fig. 1

$$\tilde{C}' = 1 - 128/a^2 e^4. \quad (16)$$

The region of possible values of $\tilde{j}$ is also bounded by the quantity $\tilde{j}'$ corresponding to $\tilde{C}'$. The extrema of $\tilde{C}'$ of all curves of the family $\tilde{C}(n_0)$ lie at $n_0 = e^4$. As n_0 changes from 1 to e^4 , $\tilde{C}$ changes from 1 to $\tilde{C}'$, and $\tilde{j}$ from 0.688 to $\tilde{j}'$; with further increase of n_0 , the same segment of the curve $\tilde{C}(\tilde{j})$ is traversed in the reverse direction.

Let us consider $a_{\text{cr}} = 8\sqrt{2}e^{-2}$. For $a < a_{\text{cr}}$, $\tilde{C}(\tilde{j})$ vanishes twice at the point $|\tilde{j}| = 1.825$, once decreasing and the second time increasing. The corresponding roots n_{01} and n_{02} are determined from the equation

$$\ln^4 n_0 = 2a^2 n_0. \quad (17)$$

For $a = a_{\text{cr}}$, $n_{01} = n_{02} = e^4$, and for $a > a_{\text{cr}}$ $\tilde{C}$ remains positive for all values of n_0 .

The investigation carried out of the functional relation between n_0 , $\tilde{C}$, and $\tilde{j}$ makes it possible to easily construct the family of curves $C(j)$, determined by equation (10) (right-hand side of Fig. 2). The transition from $\tilde{j}$ and $\tilde{C}$ to j and C for a given a is accomplished by means of formulas (14). The roots of $C(j)$ for $a < a_{\text{cr}}$ are

Fig. 1

$$|j_1| = 1.825 n_{01}^{3/2}; \quad |j_2| = 1.825 n_{02}^{3/2}. \quad (18)$$

Since as $n_0 \rightarrow \infty$, $\tilde{C} \rightarrow 1$, and $|\tilde{j}| \rightarrow 0.688$, asymptotically $C \rightarrow n_0$, while $|j| \rightarrow 0.688 n_0^{3/2} \approx 0.688 C^{3/2}$; hence it follows that the common asymptote of the family $C(j)$ is the curve

$$C = 1.284 |j|^{2/3}. \quad (19)$$

In Fig. 2 on the left the family of curves $C(n_0)$ is shown:

$$C = n_0 - \frac{1}{2a^2} \ln^4 n_0. \quad (20)$$

Let us note that, in addition to $a = a_{\text{cr}} = 1.53$, at which C becomes positive everywhere, there is one more special value, $a'_{\text{cr}} = 1.64$, at which the extrema on

Fig. 2.

Figure 2: Fig. 2.

the curves $C(n_0)$ and $C(j)$ disappear, and these curves become monotonically increasing.

Let us also note that, for the graphical representation of the dependences under study in different ranges of values of C , a uniform scale is used along the ordinate axis in the region $|C| < 1$, and a logarithmic scale in the regions $|C| > 1$.

By comparing the values of n_0 and j corresponding to one and the same C , we can find the dependence of the emission current in the dielectric on the boundary concentration n_0 and on the magnitude of the electric field at the cathode E_1 .

3. Knowledge of the functions $C(j; a)$ makes it possible to obtain in explicit form the general solution (4) of the kinetic problem and to find the current-voltage characteristics of emission currents in the dielectric with allowance for the Schottky effect. The radical changes in the function $C(j)$, caused by the action of the field on the contact barrier (cf. the curves $C(j)$ for $a = 0$ and $a \neq 0$ in Fig. 2), indicate that this effect plays an essential role in dielectric elec-

tronics. Let us show this explicitly by the example of currents $|j| > 10$, where the solution (4) is written in elementary functions ⁽³⁾

$$n = \sqrt{\frac{|j|}{2(x_1 + x)}}; \quad E = -\sqrt{2|j|(x_1 + x)}; \quad V = \frac{2\sqrt{2|j|}}{3} [(x_1 + L)^{3/2} - x_1^{3/2}]. \quad (21)$$

The current function entering into these formulas, $x_1(j) \equiv -C(j)/|j|$, is equal to

$$x_1 = \frac{|j|}{2} \exp \left[-\sqrt[4]{32a^2|j|x_1} \right]. \quad (22)$$

From the last expression (21) it follows that in the regions $x_1(j) \ll L$ and $x_1(j) \gg L$ the current-voltage characteristic respectively takes the form

$$|j| = \frac{9}{8} \frac{V^2}{L^3}; \quad V = \sqrt{2|j|x_1} L. \quad (23)$$

In the absence of the Schottky effect ($x_1 = |j|/2$) the first region corresponds to the SCLC regime, and the second to the ohmic regime: $j = V/L$. With

Fig. 2.

Schottky emission, the quadratic law is retained in the SCLC region, while for $x_1(j) \gg L$, from (22) and (23), instead of Ohm's law we obtain the formula

$$|j| = \frac{V}{L} \exp \sqrt{a \frac{V}{L}}, \quad (24)$$

which, following the works of Stockmann⁽⁵⁾ and Simmons⁽⁶⁾, is interpreted as an expression describing Schottky emission in a dielectric. However, the influence of the Schottky effect is not limited to removal of saturation with respect to concentration in the region of large currents, but plays a much more substantial role; in particular, Schottky emission broadens the region of applicability of the quadratic SCLC law and makes possible, in principle, the appearance of a second quadratic section after the region (24), etc. These results, caused by the change in the form of the function $C(j)$ and by its nonmonotonic character, will be considered in detail in a subsequent communication.

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